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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Flight Mechanics Technical Memorandum 447

RELATIVE WIND MEASUREMENTS ON AN FFG-7 CLASS FRIGATE

by

D.M. Blunt

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SUMMARY

During trials on HMAS Adelaide in March 1990, two tri-axial Gill anemometer arrays were mounted abeam of the helicopter hangars to provide information about the air flow in the vicinity of the flight deck. However, concerns were raised about the accuracy of the ship anemometers, and a comparison has therefore been made of the air flow measurements recorded from the Gill anemometer arrays with those recorded from the ship anemometers. Good agreement has been observed for certain relative wind directions, and this indicates that the ship anemometers were accurately measuring the prevailing wind velocities.

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CONTENTS

1. INTRODUCTION

In March 1990, First of Class Flight Trials were conducted aboard HMAS Adelaide to establish the operational envelope of the Australian S-70B-2 Seahawk helicopter from the FFG-7 class frigate. As part of these trials, two tri-axial Gill anemometer arrays, which had been calibrated in the ARL low speed wind tunnel, were mounted in the vicinity of the helicopter hangars. Air velocity measurements were simultaneously recorded from these arrays and the ship anemometers, for a variety of relative wind strengths and directions, to provide information about the air flow near the flight deck, and its relation to the air flow measured by the ship anemometers.

Subsequent to these trials, concerns were expressed about the validity of the techniques used to calibrate the ship anemometers, and consequently their accuracy was brought into question. It has therefore been decided to investigate the accuracy of the ship anemometers by comparing the different sets of air flow measurements. However, due to the large distance between the ship anemometers and the Gill anemometer arrays, it should be noted that this comparison cannot fully establish the accuracy of the ship anemometers; it can only give an indication thereof.

Details of the ship and Gill anemometer locations are given in Section 2, and of the data acquisition and processing in Section 3. The results and their discussion are presented in Sections 4 and 5 respectively.

2. ANEMOMETER LOCATIONS

On HMAS Adelaide, there are two identical propeller–vane type ship anemometers, one mounted either side of the rigging towards the top of the mast (see Figure 1). The signals from these anemometers are supplied to the bridge independently, and either signal can be selected for use by the ship instrumentation, though it is normal practice for the more windward one to be selected. During the trials, only the selected signal was recorded, and no record was kept of which anemometer it came from. It has therefore been assumed that the two ship anemometers gave nearly identical measurements, and thus that they could be considered as one anemometer. Because of this, the ship anemometers are referred to in the singular sense in Sections 3 to 5 below.

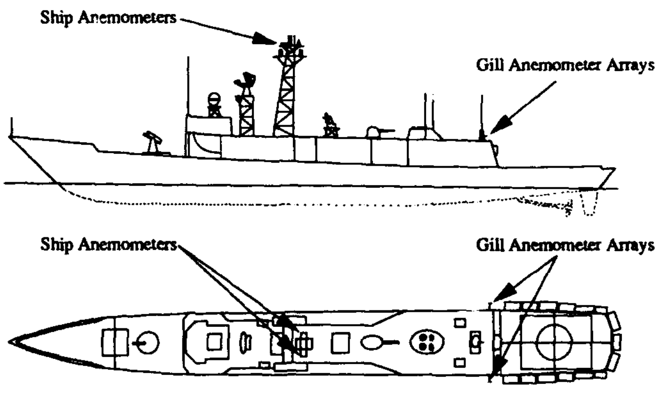

Fig. 1 Anemometer Locations

The Gill anemometer arrays were mounted on brackets which were attached perpendicularly to the aft end of the side railing along the top of the helicopter hangars (see Figure 1). Figure 2 shows the bracket on the starboard side. The three Gill anemometers in this figure point upwards, to starboard, and towards the bow. On the port side, the bracket was reversed starboard-to-port but the Gill anemometer array geometry was the same, and the port Gill anemometers pointed in the same directions as the starboard array.

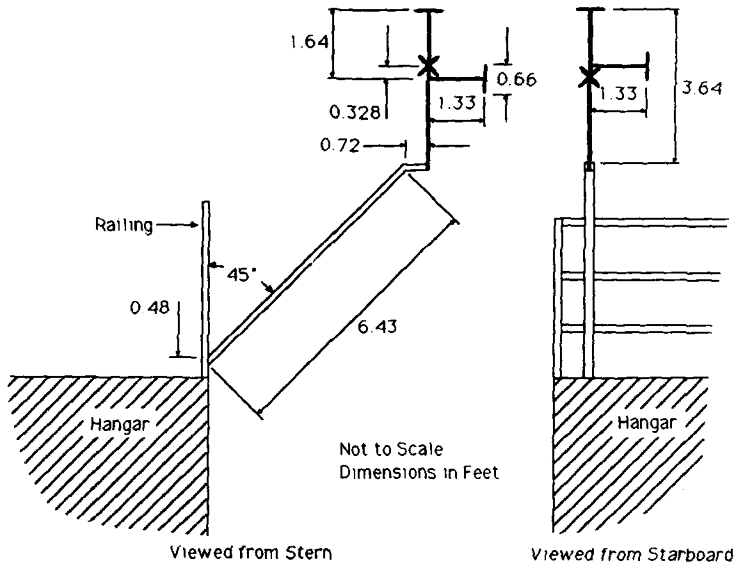

Fig. 2 Starboard Gill Anemometer Array and Mounting Bracket

3. DATA PROCESSING PROCEDURE

A data acquisition system based on a portable Compaq personal computer (PC) (Ref. 1) was used to record the measurements from the anemometers, together with the measurements from other instruments, in data files on the PC hard disk. The recordings were of various durations, depending on other aspects of the trial which are not provided here.

The raw data stored on the hard disk have been processed into engineering units by a modified version of the program 'ShipRefine' using the calibrations given in Appendix A. The original version of 'ShipRefine' was a development of the program 'Refine' (Ref. 2) that included addition code for notch digital filtering (Ref. 3) and Gill anemometer signal processing. The main modification to the program has been the correction of the Gill anemometer measurements for their non-sinusoidal response to angle of attack variation, using the iterative approach proposed by Drinkrow (Ref. 4). A more comprehensive description of the processing and the modifications is given in Ref. 5.

The processed anemometer data have been plotted in the time domain by using the general purpose data plotting program 'MacTRANS' (Ref. 6). Another program, named 'Average', has been used to calculate the mean velocity vectors and the standard deviations of the velocity magnitudes and directions (see Appendix B for equations used). The mean

velocities and standard deviations have been plotted using the commercial Macintosh graphics program 'KaleidaGraph'.

4. RESULTS

Appendix C lists all the ship based data files recorded in the trials, their overall duration, and whether the anemometer data recorded in them were suitable for analysis. Files that were deemed suitable were those with at least ten seconds of recording without any obvious noise or signal dropout on any of the anemometer data channels. Some files with intermittent or partial noise present still had usable sections of data, and the anemometer signals from a typical data file (measurement 6) exhibiting this characteristic are shown in Figure 3. Several data files were also lacking data for the port Gill anemometer array as it was not operational during those measurements.

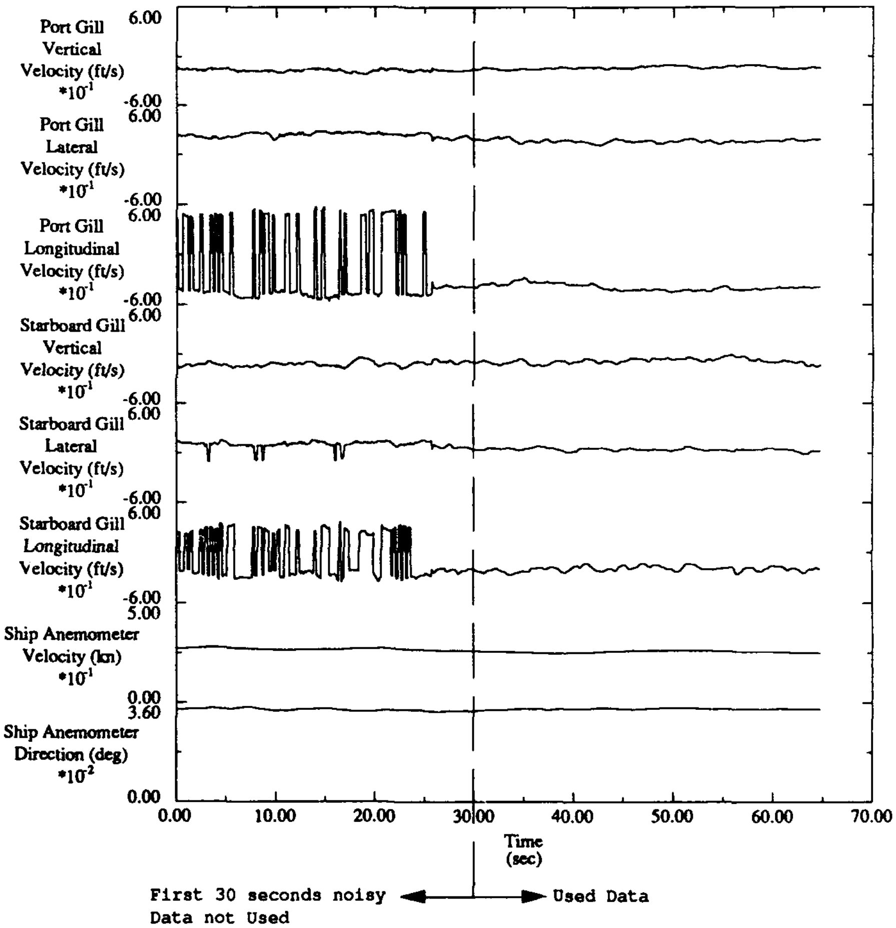

Fig. 3 Anemometer Signals from a Noisy Data File (Measurement 6)

The coordinate axes directions used in this investigation are shown in Figure 4. The wind velocity vector shown in this figure has a positive direction (i.e. from the starboard side); negative longitudinal, lateral, and vertical velocity components; and a negative vertical angle.

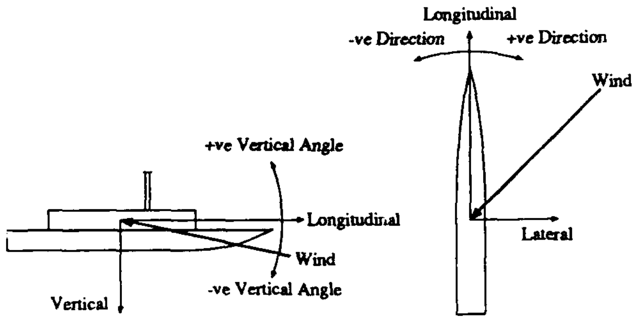

Fig. 4 Coordinate Axes Directions

It should be noted that the Gill anemometer arrays were capable of distinguishing the vertical wind velocity components from the total wind velocity vectors, while the ship anemometer was not. It has not been determined how sensitive the ship anemometer was to vertical velocity components, but it is doubtful that it would have experienced any vertical components of significance, due to its location high on the mast. Therefore, in the calculation of the mean ship anemometer velocities, it has been assumed that the average vertical velocity component was zero.

The time histories for all the measurements used in this investigation did not show any significant overall divergence from their corresponding means, and it has therefore been assumed that valid comparisons could be made of the anemometer measurements using the means and standard deviations rather than the time histories. This can be seen by comparing the time histories for the two representative cases which are shown in Figures 5 and 6 with their corresponding means and standard deviations in Appendix D. It can also be seen that Figure 5 shows good agreement between the port Gill anemometer array and the ship anemometer, and Figure 6 shows poor agreement between both Gill anemometer arrays and the ship anemometer[1]. Note, however, that both of these figures do not show the time histories of the vertical angles measured by the Gill anemometer arrays, which are dealt with in Section 5, and thus do not present a completely accurate depiction of the degree of agreement. Despite this, it can be seen that the degree of agreement in each of these measurements corresponds directly with that of the same measurements in the polar plots of the mean anemometer velocities shown in Figures 7 and 8.

The vertical angles of the mean Gill anemometer array velocities are shown in Figure 9. Figures 10 and 11 show the standard deviations of the velocity magnitudes and directions about the mean anemometer velocities.

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1 Note that a good agreement for a velocity vector requires good agreement for both magnitude and direction.

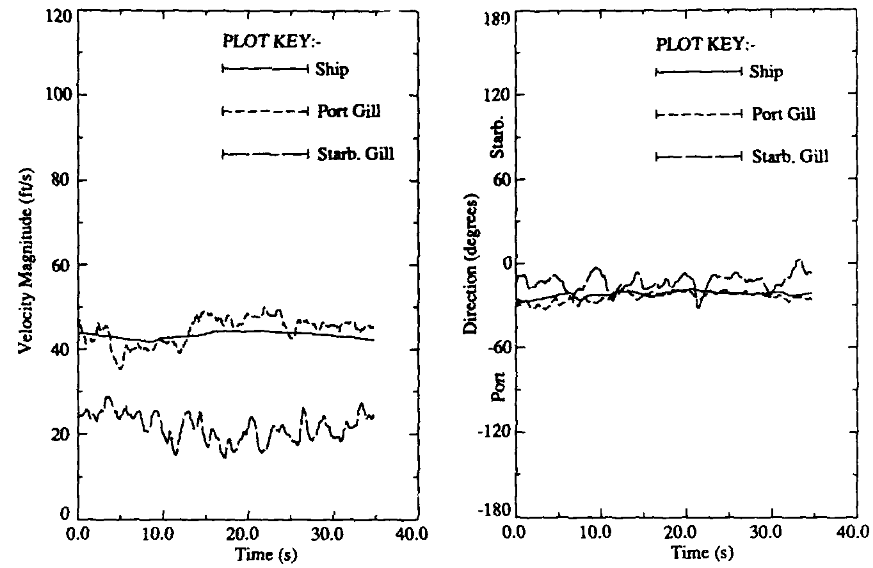

Fig. 5 Time Histories Showing Good Agreement Between the Port Gill Anemometer Array and the Ship Anemometer (Measurement 6)

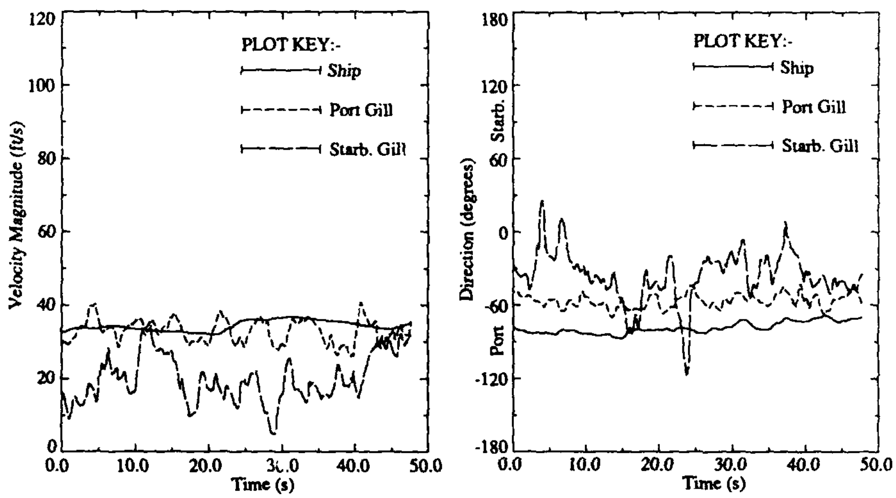

Fig. 6 Time Histories Showing Poor Agreement Between Both Gill Anemometer Arrays and the Ship Anemometer (Measurement 1)

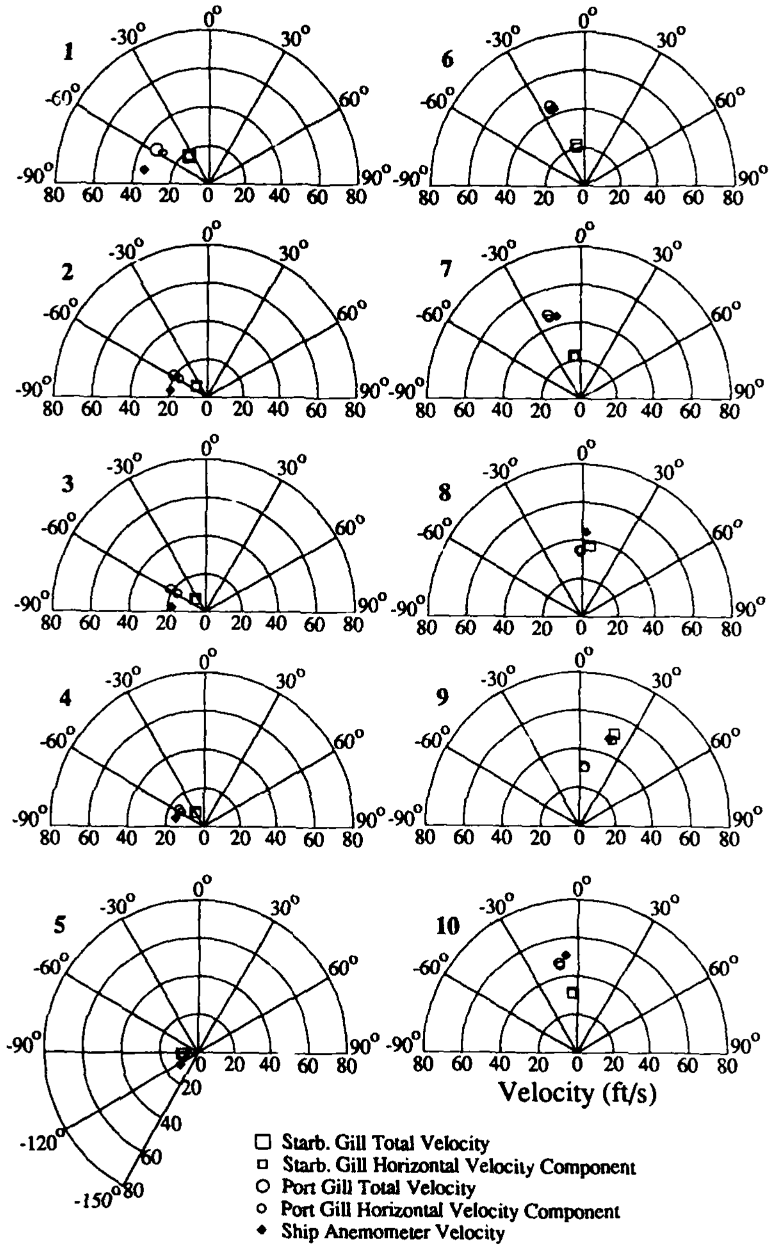

Fig. 7 Mean Anemometer Velocities (Measurements 1 – 10)

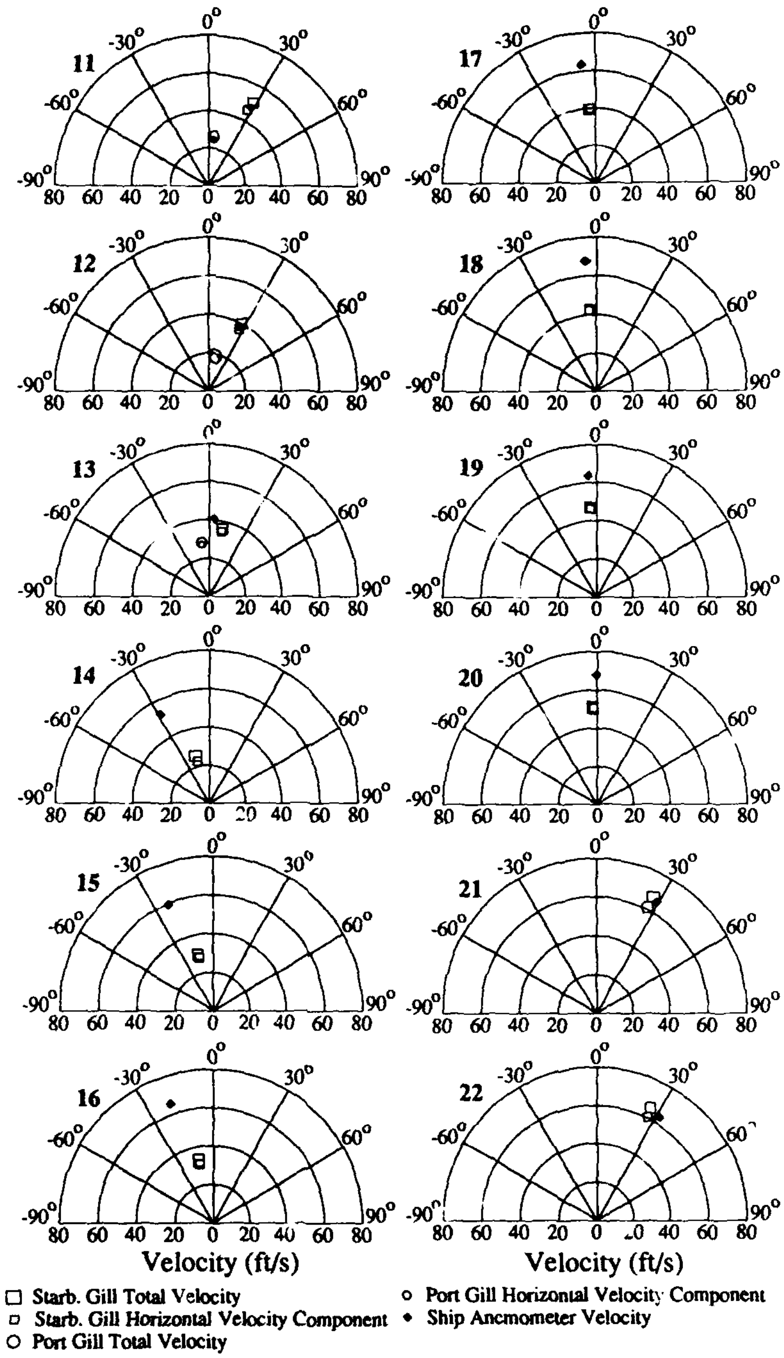

Fig. 8 Mean Anemometer Velocities (Measurements 10 – 22)

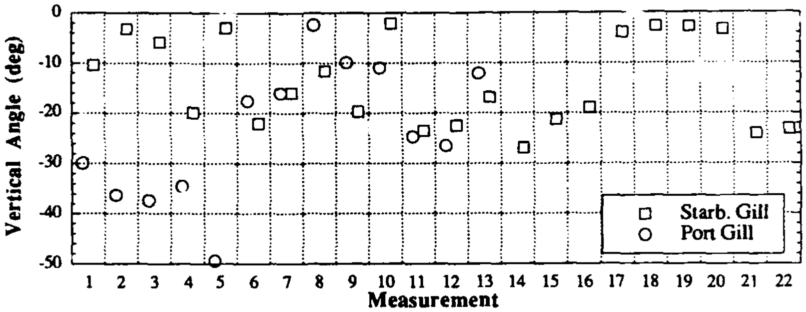

Fig. 9 Vertical Angles of Mean Velocity Vectors

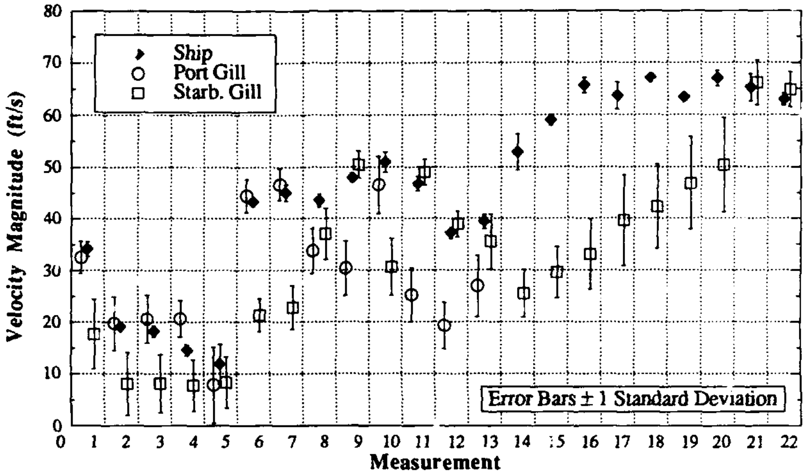

Fig. 10 Magnitudes of Mean Velocity Vectors

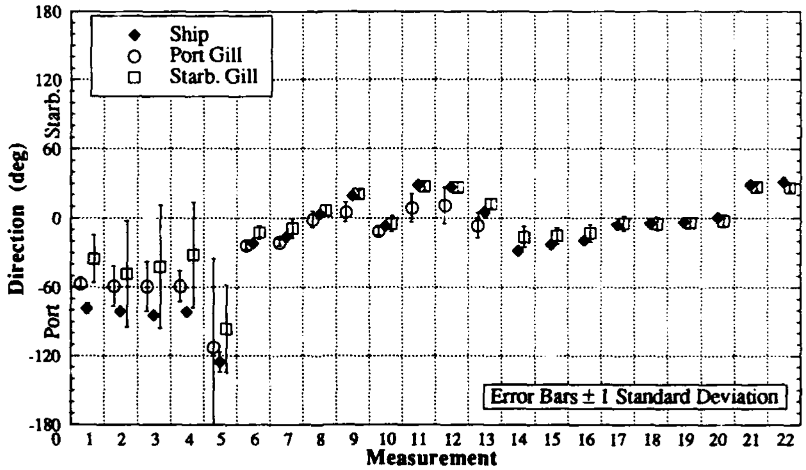

Fig. 11 Directions of Mean Velocity Vectors

5. DISCUSSION OF RESULTS

Analysis of the mean anemometer velocity vectors (Figures 7 and 8) reveals that the data only cover a small fraction of the total range of wind conditions that may be experienced. It also establishes that, if only the windward[2] Gill anemometer array is considered, good agreement exists between the mean ship anemometer velocities and the mean Gill anemometer array velocities when the relative wind direction is between approximately 15 to 30 degrees either side of the bow (measurements 6, 7, 9, 11, 12, 21, 22), that moderate agreement exists when the relative wind direction is between ±15 degrees (measurements 8, 10, 13), and that poor agreement exists for the rest of the relative wind directions[3]. This is shown diagrammatically in Figure 12.

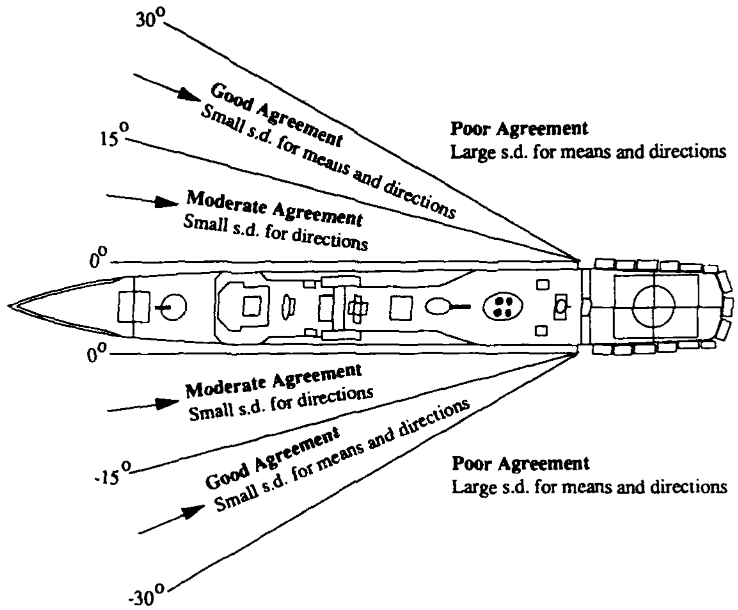

Fig. 12 Regions of Agreement Between Ship Anemometer and Gill Anemometer Arrays

Additionally, for the cases of good agreement, it can be seen from Figures 7 and 8 that the magnitudes of the mean ship anemometer velocities all fall between the magnitude of the corresponding windward mean Gill anemometer velocities and their respective horizontal components. Figure 9 also reveals that the vertical angles of these windward mean Gill anemometer array velocity vectors are between approximately -15 and -25 degrees. These results can be interpreted two ways. The first is that the winds experienced by the ship anemometer were the same as those measured by the windward Gill

2 All references to windward and leeward are based on the relative wind direction indicated by the ship anemometer.

3 Note that good, moderate, or poor agreement could not be verified for measurements 14 – 20, as the windward (port) Gill anemometer array was not operational for those measurements.

anemometer arrays, and thus that the ship anemometer was not only measuring the horizontal velocity components of the winds, but portions of the vertical velocity components as well. The second, and more likely, is that because of the close proximity of the Gill anemometer arrays to the sides of the hangars, the vertical velocity components measured by the windward Gill anemometer arrays were caused by the wind rising over the ship, and that the winds experienced by the ship anemometer, being much higher, were essentially horizontal. It follows from this second interpretation that, because the magnitudes of the mean ship anemometer velocities and the magnitudes of the mean Gill anemometer array velocities still show close agreement, the diversion of the wind over the hangars occurred with very little change to the streamwise wind velocity.

Examination of Figures 10 and 11 reveals that the standard deviations of the velocity magnitudes and directions calculated from the ship anemometer are much smaller than those calculated from the Gill anemometer arrays. The reason for this can be seen in the erratic nature of the signals from the Gill anemometer arrays, visible in the time histories in Figures 5 and 6, when compared to those from the ship anemometer. These differences indicate that the level of large-scale wind turbulence experienced by the ship anemometer may have been much lower than that experienced by the Gill anemometer arrays. However, other factors such as the shorter response time of the Gill anemometer arrays, the filtering in the ship anemometer circuitry, and even the tri-axial geometry of the Gill anemometer arrays, are likely to have affected the magnitudes of the differences, and consequently enhanced this indication.

Further analysis of Figures 10 and 11 shows that the leeward Gill anemometer arrays have larger magnitude and direction standard deviations than the windward ones. This is expected, as the leeward side of the ship was likely to have experienced higher levels of large-scale wind turbulence. In addition, for the windward Gill anemometer measurements, Figure 10 shows that the direction standard deviations are markedly reduced when the relative wind direction falls between ±30 degrees (measurements 6 – 22). Figure 11 also shows a similar, but smaller, reduction in the magnitude standard deviations for the measurements where the relative wind is between 15 to 30 degrees either side of the bow (measurements 6, 7, 9, 11, 12, 21, 22), but no reduction is observed for the measurements where the relative wind falls between ±15 degrees (measurements 8, 10, 13). These observations suggest that the "cleanest" wind (least affected by the presence of the ship) experienced by the windward Gill anemometer arrays blew from between 15 to 30 degrees either side of the bow: outside ±30 degrees the wind direction and magnitude varied considerably, and inside ±15 degrees the wind magnitude also showed more variance (see Figure 12). This correlates well with the observed good agreement between the ship anemometer and Gill anemometer arrays shown in Figures 7 and 8. The alternative explanation of these observations is that the prevailing wind turbulence varied considerably between the measurements and that this coincidentally caused the measurements to give these indications, but this is unlikely as measurements 1 to 13 were all recorded within 171 minutes, and measurements 14 to 22 were recorded on the next day within 65 minutes.

6. CONCLUDING REMARKS

The good agreement observed between the mean velocities measured by the windward Gill anemometer array and the ship anemometers when the relative wind directions were between 15 to 30 degrees either side of the bow implies that they were both measuring close to the same wind conditions in those cases. This is despite the mean Gill anemometer array velocities in these measurements all having vertical angles between -15 and -25

degrees, which appears to be due to the wind rising over the ship with very little change to its streamwise velocity. The smaller velocity magnitude and direction standard deviations for the windward Gill anemometer array measurements in these cases also implies that they were taken in wind least affected by the presence of the ship and thus closest to the prevailing wind conditions. Therefore, as the Gill anemometer arrays were accurately calibrated, this gives a strong indication that the ship anemometers were accurately measuring the prevailing wind velocities from these directions. It is also reasonable to assume from this that the ship anemometers accurately measure the prevailing wind velocities from all directions, as they are positioned in locations where they are more likely to do so than the Gill anemometer arrays.

The disparity between the results for the rest of the measurements shows that in those cases the Gill anemometer arrays were not measuring the prevailing wind conditions. Given the proximity of the Gill anemometer arrays to the bluff shaped hangars, this is not unexpected.

The comparison presented in this document is by no means a completely thorough examination of the accuracy of the ship anemometers. The positioning of the Gill anemometer arrays is too distant from the ship anemometers, and too close to the hangars, for that. If a stricter test of the accuracy is required then a new experiment should be performed with a Gill anemometer array mounted on the mast near the ship anemometers. It should also be noted that ocean boundary layer affects, brought about by the relative height difference between the ship anemometers and the Gill anemometer arrays, may have been responsible for some of the differences observed, but they have not been considered here.

ACKNOWLEDGEMENT

The author wishes to acknowledge the work of Dr D.J. Sherman who wrote the subroutines used to correct the non-sinusoidal response of the Gill anemometer arrays to angle of attack variation.

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3. Perrin, R.H., and Feik, R.A., "Application of a Notch Digital Filter to Elimination of Sinusoidal Disturbances from Helicopter Flight Data," *ARL-AERO-TM-382*, April 1986.

4. Drinkrow, R., "A Solution to the Paired Gill-Anemometer Response Function," *Journal of Applied Meteorology*, Vol. 11, February 1972, pp. 76-80.

5. Blunt, D.M., "An Investigation into the Accuracy of the Anemometers on an FFG-7 Class Frigate," *ARL Group Report RW 91/4 (unpublished)*, August 1991.

6. Blunt, D.M., "The Conversion of a Fortran Data Plotting Program Using DI-3000 Graphics to Operation on a Macintosh Personal Computer," *ARL-FLIGHT-MECH-TM-446*, September 1991.

APPENDIX A

Calibrations Used in 'ShipRefine'

A.1 Calibration File Used in 'ShipRefine'

```
TITLE (2 lines of 60 chrs)
Calibration file for FOCFT/ship/
data.
[Channel no. -1 denotes time]
```

Channel No.	Label	Cal Factor, Offset	Assigned No.	Plot Limits (Lower, Upper)
-1	Time	5.0000E-02		
	(s)	0.0000E+00		
1	spare	0.0000E+00	18	-5.0000E+00
		0.0000E+00		5.0000E+00
2	spare	0.0000E+00	50	-5.0000E+00
		0.0000E+00		5.0000E+00
3	spare	0.0000E+00	51	-5.0000E+00
		0.0000E+00		5.0000E+00
4	spare	0.0000E+00	600	-5.0000E+00
		0.0000E+00		5.0000E+00
5	Pitch	6.1035E-03	32	-1.0000E+01
	(degrees)	0.5280E+00		1.0000E+01
6	Roll	2.2827E-02	33	-1.0000E+01
	(degrees)	-0.0840E+00		1.0000E+01
7	Heave Acc	2.2780E-02	35	-4.0000E+01
	(ft/s**2)	0.0000E+00		4.0000E+01
8	Sway Acc	1.8066E-02	36	-4.0000E+01
	(ft/s**2)	0.0000E+00		4.0000E+01
9	Lat Acc	3.5348E-02	37	-4.0000E+01
	(ft/s**2)	0.0000E+00		4.0000E+01
10	Vert Acc	3.5348E-02	38	-4.0000E+01
	(ft/s**2)	0.0000E+00		4.0000E+01
11	spare	0.0000E+00	39	-5.0000E+00
		0.0000E+00		5.0000E+00
12	Long Acc	3.5348E-02	40	-4.0000E+01
	(ft/s**2)	0.0000E+00		4.0000E+01
13	Temp Port	2.4410E-03	19	-5.0000E+00
	(volts)	0.0000E+00		5.0000E+00
14	Temp Starb	2.4410E-03	20	-5.0000E+00
	(volts)	0.0000E+00		5.0000E+00
15	spare	0.0000E+00	21	-5.0000E+00
		0.0000E+00		5.0000E+00
16	spare	0.0000E+00	52	-5.0000E+00
		0.0000E+00		5.0000E+00
17	spare	0.0000E+00	53	-5.0000E+00
		0.0000E+00		5.0000E+00
18	spare	0.0000E+00	54	-5.0000E+00
		0.0000E+00		5.0000E+00
19	spare	0.0000E+00	55	-5.0000E+00
		0.0000E+00		5.0000E+00
20	Wind Vel	2.4410E-03	1	-6.0000E+01
	P1 (ft/s)	0.0000E+00		6.0000E+01
21	Wind Vel	2.4410E-03	2	-6.0000E+01
	P2 (ft/s)	0.0000E+00		6.0000E+01
22	Wind Vel	2.4410E-03	3	-6.0000E+01
	P3 (ft/s)	0.0000E+00		6.0000E+01
23	Wind Vel	2.4410E-03	4	-6.0000E+01

	S1 (ft/s)	0.0000E+00		6.0000E+01
24	Wind Vel	2.4410E-03	5	-6.0000E+01
	S2 (ft/s)	0.0000E+00		6.0000E+01
25	Wind Vel	2.4410E-03	6	-6.0000E+01
	S3 (ft/s)	0.0000E+00		6.0000E+01
26	spare	0.0000E+00	7	-5.0000E+00
		0.0000E+00		5.0000E+00
27	spare	0.0000E+00	8	-5.0000E+00
		0.0000E+00		5.0000E+00
28	spare	0.0000E+00	9	-5.0000E+00
		0.0000E+00		5.0000E+00
29	spare	0.0000E+00	30	-5.0000E+00
		0.0000E+00		5.0000E+00
30	spare	0.0000E+00	31	-5.0000E+00
		0.0000E+00		5.0000E+00
31	spare	0.0000E+00	601	-5.0000E+00
		0.0000E+00		5.0000E+00
32	spare	0.0000E+00	602	-5.0000E+00
		0.0000E+00		5.0000E+00
33	Wind Dir	1.0000E+00	10	-1.0000E+00
	Port 1	0.0000E+00		1.0000E+00
34	Wind Dir	1.0000E+00	11	-1.0000E+00
	Port 2	0.0000E+00		1.0000E+00
35	Wind Dir	1.0000E+00	12	-1.0000E+00
	Port 3	0.0000E+00		1.0000E+00
36	Wind Dir	1.0000E+00	13	-1.0000E+00
	Starb 1	0.0000E+00		1.0000E+00
37	Wind Dir	1.0000E+00	14	-1.0000E+00
	Starb 2	0.0000E+00		1.0000E+00
38	Wind Dir	1.0000E+00	15	-1.0000E+00
	Starb 3	0.0000E+00		1.0000E+00
39	Event	1.0000E+00	16	-1.0000E+00
	Marker	0.0000E+00		1.0000E+00
40	Crctd Wind	1.0000E+00	17	-6.0000E+01
	P1 (ft/s)	0.0000E+00		6.0000E+01
41	Crctd Wind	1.0000E+00	603	-6.0000E+01
	P2 (ft/s)	0.0000E+00		6.0000E+01
42	Crctd Wind	1.0000E+00	604	-6.0000E+01
	P3 (ft/s)	0.0000E+00		6.0000E+01
43	Crctd Wind	1.0000E+00	605	-6.0000E+01
	S1 (ft/s)	0.0000E+00		6.0000E+01
44	Crctd Wind	1.0000E+00	606	-6.0000E+01
	S2 (ft/s)	0.0000E+00		6.0000E+01
45	Crctd Wind	1.0000E+00	607	-6.0000E+01
	S3 (ft/s)	0.0000E+00		6.0000E+01
46	Exact	1.0000E+00	608	0.0000E+00
	Start Time	0.0000E+00		6.0000E+01
47	Gill P.Vel	1.0000E+00	609	0.0000E+00
	(ft/s)	0.0000E+00		1.2000E+02
48	Gill P.Dir	1.0000E+00	610	-1.8000E+02
	(deg)	0.0000E+00		1.8000E+02
49	Gill S.Vel	1.0000E+00	611	0.0000E+00
	(ft/s)	0.0000E+00		1.2000E+02
50	Gill S.Dir	1.0000E+00	612	-1.8000E+02
	(deg)	0.0000E+00		1.8000E+02
51	Ship Dir	5.4932E-03	603	-1.8000E+02
	(deg)	0.0000E+00		1.8000E+02
52	Ship Anem	2.5754E-03	604	0.0000E+00
	Vel (ft/s)	0.0000E+00		1.2000E+02
53	Ship Vel	6.1035E-04	605	0.0000E+00
	(kn)	-0.4000E+00		3.0000E+01
54	Ship Anem	5.4932E-03	606	-1.8000E+02
	Dir (deg)	0.0000E+00		1.8000E+02

A.2 Gill Anemometer Calibrations

The Gill anemometer calibrations given in Section A.1 convert the Gill anemometer signals to volts only. The following equations represent the calculations used in 'ShipRefine' to convert the signals to ft/s. The separate equations for vertical, lateral, and longitudinal anemometers are used because of different gains applied to each signal.

a) Conversion of voltage to frequency

Vertical	$f_{vert} = 0.1768 + 105.33 \times V_{vert}$ Hz
Lateral	$f_{lat} = 1.4568 + 180.91 \times V_{lat}$ Hz
Longitudinal	$f_{long} = 3.8762 + 346.35 \times V_{long}$ Hz

b) Conversion of frequency to ft/s

The calibration factor was obtained as a function of frequency and direction by interpolation from Table A.1.

TABLE A1
Calibration of Gill 4-blade Propellor Anemometers

Frequency (Hz)	**Calibration (m/s/Hz)**	
	In-to-wind	Away-from-wind
25	0.0267	0.0289
50	0.0261	0.0279
75	0.0258	0.0275
100	0.0257	0.0272
150	0.0257	0.0270
200	0.0257	0.0270
500	0.0256	0.0270

Each frequency was then multiplied by its calibration factor and converted to ft/s using the equation

$$\text{Velocity} = f \times \text{Cal} \times 3.2808 \text{ ft/s}$$

APPENDIX B

Equations Used in 'Average'

The coordinate axes directions used in 'Average' are the same as those shown in Figure 4.

'Average' reads .COL files produced by 'MacTRANS' with a maximum of six columns, and expects to see the data they contain in the format set out in Table B1.

TABLE B1
Anemometer Velocity Components Format Needed by Program 'Average'

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Time Channel	Gill Vertical Component $v_{i,vert}$	Gill Lateral Component $v_{i,lat}$	Gill Longitudinal Component $v_{i,long}$	Ship Anemometer Magnitude $\lvert\vec{v}_{i,ship}\rvert$	Ship Anemometer Direction $\angle\vec{v}_{i,ship}$

'Average' computes the averages and standard deviations of the data in columns 2 – 6 using the formulae

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad\qquad s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

The averages of columns 2 to 4 are used to compute the mean Gill anemometer array (GAA) velocity, and the averages of columns 3 and 4 are used to compute the horizontal component of the mean Gill anemometer array velocity, using the formulae

Magnitude of Mean GAA Velocity Vector	$\lvert\vec{v}\rvert = \sqrt{\bar{v}_{long}^2 + \bar{v}_{lat}^2 + \bar{v}_{vert}^2}$
Horiz. Comp. of Mean GAA Velocity Vector	$\lvert\vec{v}\rvert_{horiz} = \sqrt{\bar{v}_{long}^2 + \bar{v}_{lat}^2}$
Direction (in horiz. plane) of Mean GAA Velocity Vector Note: this expression is equivalent to using the Fortran intrinsic function Z = ATAN2(-X,-Y) where $X = \bar{v}_{lat}$ $Y = \bar{v}_{long}$ $Z = \angle\vec{v}$	$\angle\vec{v} = \begin{cases} \tan^{-1}\left(\frac{\bar{v}_{lat}}{\bar{v}_{long}}\right) & \bar{v}_{long} < 0 \\ \tan^{-1}\left(\frac{\bar{v}_{lat}}{\bar{v}_{long}}\right) - \pi & \bar{v}_{long} > 0, \bar{v}_{lat} > 0 \\ \tan^{-1}\left(\frac{\bar{v}_{lat}}{\bar{v}_{long}}\right) + \pi & \bar{v}_{long} > 0, \bar{v}_{lat} \le 0 \\ \frac{\pi}{2} & \bar{v}_{long} = 0, \bar{v}_{lat} < 0 \\ -\frac{\pi}{2} & \bar{v}_{long} = 0, \bar{v}_{lat} > 0 \\ 0 & \bar{v}_{long} = 0, \bar{v}_{lat} = 0 \end{cases}$

Vertical Angle of Mean GAA Velocity Vector Note: this expression is equivalent to using the Fortran intrinsic function Z = ATAN2(-X,-Y) where $X = \bar{v}_{vert}$ $Y = \lvert \vec{v} \rvert_{horiz}$ $Z = \angle\vec{v}$	$\angle\vec{v}_{vert} = \begin{cases} \tan^{-1}\left(\dfrac{\bar{v}_{vert}}{\lvert \vec{v} \rvert_{horiz}}\right) & \lvert \vec{v} \rvert_{horiz} > 0 \\ \dfrac{\pi}{2} & \lvert \vec{v} \rvert_{horiz} = 0,\ \bar{v}_{vert} > 0 \\ -\dfrac{\pi}{2} & \lvert \vec{v} \rvert_{horiz} = 0,\ \bar{v}_{vert} < 0 \\ 0 & \lvert \vec{v} \rvert_{horiz} = 0,\ \bar{v}_{vert} = 0 \end{cases}$

The mean ship anemometer (SA) velocity is calculated by using the velocity magnitudes and directions to calculate the longitudinal and lateral velocity components, and then averaging these components to arrive at the mean velocity vector using the formulae*

Average Long. Comp. of SA Velocity Vectors	$\bar{v}_{ship\ long} = \frac{1}{n}\sum_{i=1}^{n}\left(-\lvert \vec{v}_{i,ship} \rvert \times \cos\left(\angle\vec{v}_{i,ship}\right)\right)$ Note: negative sign is due to coordinate axes system
Average Lat. Comp. of SA Velocity Vectors	$\bar{v}_{ship\ lat} = \frac{1}{n}\sum_{i=1}^{n}\left(-\lvert \vec{v}_{i,ship} \rvert \times \sin\left(\angle\vec{v}_{i,ship}\right)\right)$ Note: negative sign is due to coordinate axes system
Magnitude of Mean SA Velocity Vector	$\lvert \vec{v}_{ship} \rvert = \sqrt{\bar{v}^2_{ship\ long} + \bar{v}^2_{ship\ lat}}$
Direction of Mean SA Velocity Vector Note: this expression is equivalent to using the Fortran intrinsic function Z = ATAN2(-X,-Y) where $X = \bar{v}_{ship\ lat}$ $Y = \bar{v}_{ship\ long}$ $Z = \angle\vec{v}_{ship}$	$\angle\vec{v}_{ship} = \begin{cases} \tan^{-1}\left(\dfrac{\bar{v}_{ship\ lat}}{\bar{v}_{ship\ long}}\right) & \bar{v}_{ship\ long} < 0 \\ \tan^{-1}\left(\dfrac{\bar{v}_{ship\ lat}}{\bar{v}_{ship\ long}}\right) - \pi & \bar{v}_{ship\ long} > 0,\ \bar{v}_{ship\ lat} > 0 \\ \tan^{-1}\left(\dfrac{\bar{v}_{ship\ lat}}{\bar{v}_{ship\ long}}\right) + \pi & \bar{v}_{ship\ long} > 0,\ \bar{v}_{ship\ lat} \le 0 \\ \dfrac{\pi}{2} & \bar{v}_{ship\ long} = 0,\ \bar{v}_{ship\ lat} < 0 \\ -\dfrac{\pi}{2} & \bar{v}_{ship\ long} = 0,\ \bar{v}_{ship\ lat} > 0 \\ 0 & \bar{v}_{ship\ long} = 0,\ \bar{v}_{ship\ lat} = 0 \end{cases}$

* The assumption here is that the velocity vectors measured by the ship anemometer have an average vertical velocity component equal to zero, and thus that they are totally represented by the velocity magnitudes and directions in columns 5 and 6. This was necessary because the ship anemometer cannot differentiate the vertical velocity component from the overall velocity measurement. The assumption is reasonable though, considering that the location of the ship anemometer (high on the mast) is not likely to give rise to a large non-zero average vertical velocity component.

'Average' also computes the standard deviations (SD) of the velocity vector magnitudes and directions about the corresponding mean velocity vector components for each anemometer using the formulae

SD of SA Velocity Vector Magnitudes about Magnitude of Mean SA Velocity Vector	$s\lvert\vec{v}_{ship}\rvert = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\lvert\vec{v}_{i,ship}\rvert - \lvert\vec{v}_{ship}\rvert\right)^2}$
SD of SA Velocity Vector Directions about Direction of Mean SA Velocity Vector Note: these equations ensure that the angular difference is less than or equal to π, i.e. the smaller angle between the velocity vectors.	$s\angle\vec{v}_{ship} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} A_{i,ship}^2}$ where $A_{i,ship} = \left\lvert B_{i,ship} + \begin{cases} -2\pi & B_{i,ship} > \pi \\ 0 & B_{i,ship} \le \pi \end{cases} \right\rvert$ $B_{i,ship} = \lvert \angle\vec{v}_{i,ship} - \angle\vec{v}_{ship} \rvert$ Note: $-\pi \le \angle\vec{v}_{i,ship} \le \pi$ and $-\pi < \angle\vec{v}_{ship} \le \pi$
SD of GAA Velocity Vector Magnitudes about Magnitude of Mean GAA Velocity Vector	$s\lvert\vec{v}\rvert = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\sqrt{v_{i,long}^2 + v_{i,lat}^2 + v_{i,vert}^2} - \lvert\vec{v}\rvert\right)^2}$
SD of GAA Velocity Vector Directions about Direction of Mean GAA Velocity Vector Note: these equations ensure that the angular difference is less than or equal to π, i.e. the smaller angle between the velocity vectors. Also, the last expression is equivalent to using the Fortran intrinsic function Z = ATAN2(-X,-Y) where $X = v_{i,lat}$ $Y = v_{i,long}$ $Z = \angle\vec{v}_i$	$s\angle\vec{v} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} A_i^2}$ where $A_i = \left\lvert B_i + \begin{cases} -2\pi & B_i > \pi \\ 0 & B_i \le \pi \end{cases} \right\rvert$ $B_i = \lvert \angle\vec{v}_i - \angle\vec{v} \rvert$ $\angle\vec{v}_i = \begin{cases} \tan^{-1}\left(\frac{v_{i,lat}}{v_{i,long}}\right) & v_{i,long} < 0 \\ \tan^{-1}\left(\frac{v_{i,lat}}{v_{i,long}}\right) - \pi & v_{i,long} > 0,\ v_{i,lat} > 0 \\ \tan^{-1}\left(\frac{v_{i,lat}}{v_{i,long}}\right) + \pi & v_{i,long} > 0,\ v_{i,lat} \le 0 \\ \frac{\pi}{2} & v_{i,long} = 0,\ v_{i,lat} < 0 \\ -\frac{\pi}{2} & v_{i,long} = 0,\ v_{i,lat} > 0 \\ 0 & v_{i,long} = 0,\ v_{i,lat} = 0 \end{cases}$ Note: $-\pi < \angle\vec{v}_i \le \pi$ and $-\pi < \angle\vec{v} \le \pi$

Example of Output from Program Average

The following example shows the format of the output from Average. It uses, as an input file, a .COL file derived from the data file 26032130.DAT.

```
26032130.DAT


RECORDED ON 03-MAY-91   AT 16:46:13   INTEGN INT = 0.0000E+00
                                       RUN CPU TIME =   3 MIN. 16.07 SEC

BLK NUMBER =   43          44          45          52          54
 Time        Crctd Wind  Crctd Wind  Crctd Wind  Ship Anem   Ship Anem
 (s)         S1 (ft/s)   S2 (ft/s)   S3 (ft/s)   Vel (kn)    Dir (deg)
 8.6900E+01 -1.0364E+01 -7.1246E+00 -3.3289E+01  2.3377E+01  3.4560E+01
std. dev's    3.0254662   2.1690753   5.6951284   0.7818196  96.4678268

Number of time samples =     1739.000

Mean vector total magnitude =    35.58524     ft/s
Mean vector horizontal magnitude =    34.04259     ft/s
Mean vector wind direction (in horizontal plane) =    12.08051     deg
Mean vector wind direction vertical angle =   -16.93237     deg

Mean ship anemometer velocity vector magnitude =    39.37938     ft/s
Mean ship anemometer velocity vector direction =    5.007875     deg
Stand. dev. of the ship vector magnitudes about the mean ship vector magnitude
 =  1.321830     ft/s
Stand. dev. of the ship vector directions about the mean ship vector direction
=   3.602886     degrees

Stand. dev. of the Gill vector magnitudes about the mean vector magnitude =
   5.323363     ft/s
Stand. dev. of the Gill vector directions about the mean vector direction =
   3.816804     degrees
```

APPENDIX C

Data Files

Data File*	Measurement	Used	Length (s)	Comments
26031002	–	×	14.80	No signal
26031839	1	✓	47.70	Good
26031846	2	✓	36.70	Good
26031854	3	✓	41.85	Good
26031857	4	✓	20.90	Good
26031932	–	×	3.80	Too short
26031943	5	✓	71.85	Good
26031958	6	✓	64.70	First 30 sec not used due to noise
26032005	–	×	69.90	Noise
26032011	–	×	153.70	Noise
26032023	7	✓	83.75	First 40 sec not used due to noise
26032033	8	✓	22.80	Good
26032046	–	×	6.65	Too short
26032051	9	✓	64.70	First 55 sec used, noise 60 sec on
26032057	10	✓	66.70	Good
26032106	11	✓	83.75	Good
26032117	12	✓	167.90	First 65 sec used, noise 70–105 sec
26032130	13	✓	146.95	First 60 sec not used due to noise
27031538	14	✓	45.70	Good, no signal port anemometers
27031543	15	✓	50.90	Good, no signal port anemometers
27031547	16	✓	59.90	Good, no signal port anemometers
27031551	17	✓	38.95	Good, no signal port anemometers
27031554	18	✓	67.65	Good, no signal port anemometers
27031601	19	✓	11.90	Good, no signal port anemometers
27031606	20	✓	25.70	Good, no signal port anemometers
27031625	–	×	67.65	Noise
27031630	21	✓	65.70	Good, no signal port anemometers
27031643	22	✓	22.75	Good, no signal port anemometers
27031645	–	×	2.85	Too short
31031048	–	×	491.95	No signal / noise
31031136	–	×	393.95	No signal / noise
03040758	–	×	361.65	No signal
03041500	–	×	1.65	No signal
03041502	–	×	134.35	No signal
03041505	–	×	66.30	No signal
Inhangar	–	×	416.00	No signal / noise

* The naming system used for the data files uses the format: Day, Month, Time (e.g. 26031002 means the file was recorded on the 26 March at 10:02).

APPENDIX D

Calculated Anemometer Data

TABLE D1
Ship Anemometer Mean Velocities and Standard Deviations

Measurement	$\lvert\vec{v}_{ship}\rvert$ (ft/s)	$s_{\lvert\vec{v}_{ship}\rvert}$ (ft/s)	$\angle\vec{v}_{ship}$ (deg)	$s_{\angle\vec{v}_{ship}}$ (deg)
1	34.18	1.41	-78.57	4.75
2	19.10	0.76	-80.92	2.52
3	18.26	1.13	-84.28	3.38
4	14.56	1.05	-81.34	1.14
5	11.88	3.82	-125.54	8.92
6	43.29	0.74	-21.96	2.07
7	45.01	1.55	-16.56	2.99
8	43.55	1.23	3.37	1.97
9	47.95	0.89	18.86	3.36
10	50.90	1.97	-7.01	1.27
11	46.78	1.39	28.79	3.26
12	37.22	1.09	26.89	2.88
13	39.38	1.32	5.01	3.60
14	52.80	3.47	-28.45	2.93
15	58.96	1.04	-23.04	2.08
16	65.66	1.42	-19.43	1.49
17	63.65	2.65	-6.20	2.12
18	67.05	0.76	-4.82	1.16
19	63.34	0.33	-3.75	0.91
20	67.00	1.45	0.26	2.38
21	65.23	2.61	29.11	3.18
22	62.95	1.16	31.24	3.10

$\lvert\vec{v}_{ship}\rvert$ Magnitude of mean ship anemometer velocity vector

$s_{\lvert\vec{v}_{ship}\rvert}$ Standard deviation of ship anemometer velocity vector magnitude about magnitude of mean ship anemometer velocity vector

$\angle\vec{v}_{ship}$ Direction of mean ship anemometer velocity vector

$s_{\angle\vec{v}_{ship}}$ Standard deviation of ship anemometer velocity vector direction about direction of mean ship anemometer velocity vector

TABLE D2
Port Gill Anemometer Array Mean Velocities and Standard Deviations

Measure-ment	$\lvert\vec{v}\rvert$ (ft/s)	$\lvert\vec{v}\rvert_{horiz}$ (ft/s)	$s_{\lvert\vec{v}\rvert}$ (ft/s)	$\angle\vec{v}$ (deg)	$s_{\angle\vec{v}}$ (deg)	$\angle\vec{v}_{vert}$ (deg)
1	32.59	28.26	3.12	-56.77	5.52	-29.9
2	19.75	15.91	5.20	-59.01	17.30	-36.3
3	20.63	16.39	4.60	-59.20	21.47	-37.4
4	15.64	12.89	3.54	-58.11	13.39	-34.5
5	7.86	5.12	7.33	-112.33	76.99	-49.4
6	44.40	42.26	3.23	-23.73	3.37	-17.9
7	46.64	44.80	3.04	-21.09	2.86	-16.1
8	33.75	33.72	4.35	-1.25	7.06	-2.4
9	30.39	29.94	5.27	5.07	8.52	-9.9
10	46.54	45.69	5.50	-11.50	3.84	-11.0
11	25.21	22.91	5.18	8.84	12.41	-24.7
12	19.31	17.28	4.49	11.06	15.75	-26.5
13	26.93	26.32	5.97	-6.62	11.03	-12.1

$\lvert\vec{v}\rvert$ Magnitude of mean Gill anemometer array velocity vector

$\lvert\vec{v}\rvert_{horiz}$ Magnitude of horizontal component of mean Gill anemometer array velocity vector

$s_{\lvert\vec{v}\rvert}$ Standard deviation of Gill anemometer array velocity vector magnitude about magnitude of mean Gill anemometer array velocity vector

$\angle\vec{v}$ Direction of mean Gill anemometer array velocity vector

$s_{\angle\vec{v}}$ Standard deviation of Gill anemometer array velocity vector direction about direction of mean Gill anemometer array velocity vector

$\angle\vec{v}_{vert}$ Vertical angle of mean Gill anemometer array velocity vector

TABLE D3
Starboard Gill Anemometer Array Mean Velocities and Standard Deviations

Measure-ment	$\lvert\vec{v}\rvert$ (ft/s)	$\lvert\vec{v}\rvert_{horiz}$ (ft/s)	$s_{\lvert\vec{v}\rvert}$ (ft/s)	$\angle\vec{v}$ (deg)	$s_{\angle\vec{v}}$ (deg)	$\angle\vec{v}_{vert}$ (deg)
1	17.71	17.42	6.75	-35.55	20.57	-10.4
2	8.04	8.03	6.06	-48.57	46.06	-3.2
3	8.17	8.13	5.60	-42.40	53.19	-5.8
4	7.79	7.32	4.96	-32.02	45.67	-19.9
5	8.32	8.32	4.94	-96.31	38.26	-2.9
6	21.37	19.82	3.21	-12.58	5.79	-22.0
7	22.87	21.99	4.21	-9.21	8.07	-16.0
8	37.06	36.30	4.99	6.20	4.70	-11.6
9	50.47	47.51	2.59	20.66	3.27	-19.7
10	30.6[illegible]	30.60	5.53	-4.99	6.82	-2.1
11	49.01	44.95	2.48	27.45	3.71	-23.5
12	38.96	35.98	2.52	26.69	4.35	-22.5
13	35.59	34.04	5.32	12.08	3.82	-16.9
14	25.49	22.72	4.56	-16.47	9.14	-26.9
15	29.60	27.57	4.97	-15.42	7.03	-21.3
16	33.07	31.28	6.79	-13.28	7.59	-18.9
17	39.68	39.59	8.81	-4.84	6.43	-3.9
18	42.31	42.27	8.16	-5.02	5.70	-2.7
19	46.83	46.77	8.94	-4.28	4.43	-2.8
20	50.37	50.28	9.05	-2.62	5.25	-3.3
21	66.16	60.41	4.29	26.90	2.90	-24.0
22	64.82	59.60	3.38	26.33	2.64	-23.2

$\lvert\vec{v}\rvert$ Magnitude of mean Gill anemometer array velocity vector

$\lvert\vec{v}\rvert_{horiz}$ Magnitude of horizontal component of mean Gill anemometer array velocity vector

$s_{\lvert\vec{v}\rvert}$ Standard deviation of Gill anemometer array velocity vector magnitude about magnitude of mean Gill anemometer array velocity vector

$\angle\vec{v}$ Direction of mean Gill anemometer arrav velocity vector

$s_{\angle\vec{v}}$ Standard deviation of Gill anemometer array velocity vector direction about direction of mean Gill anemometer array velocity vector

$\angle\vec{v}_{vert}$ Vertical angle of mean Gill anemometer array velocity vector

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During trials on HMAS Adelaide in March 1990, two tri-axial Gill anemometer arrays were mounted abeam of the helicopter hangars to provide information about the air flow in the vicinity of the flight deck. However, concerns were raised about the accuracy of the ship anemometers, and a comparison has therefore been made of the air flow measurements recorded from the Gill anemometer arrays with those recorded from the ship anemometers. Good agreement has been observed for certain relative wind directions, and this indicates that the ship anemometers were accurately measuring the prevailing wind velocities.

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